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TRANSIENT RESPONSE OF A LOG-PERIODIC ANTENNA BASED ON BROAD-BAN--ETC(U)

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Transient Response of a Log-Periodic Antenna Based on Broad-Band Continuous-Wave Measurements

April 1977

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The broad-band characteristics of a very-high-frequency log-periodic antenna were determined and used to compute the response of this antenna to a transient incident electromagnetic field. The antenna characteristics were obtained from broad-band continuous-wave (CW) measurements, and the transient response was computed from Fourier analysis of the CW data. The computed transient response showed good agreement with the measured

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transient response. An approximate theoretical solution was developed based on these measurements.

CONTENTS

FIGURES

1. INTRODUCTION

1.1. Objectives

There are many types of broad-band communications antennas used as part of Army tactical communications. Some of these antennas are designed to operate at frequencies which lie within the principal frequency spectrum associated with the radiated electromagnetic pulse (EMP) from an exoatmospheric nuclear burst; consequently, a significant EMP response of such an antenna is to be expected. An example of this type of antenna is Log-periodic (LP) Antenna AS-2169, designed for operation in the frequency range of 30 to 76 MHz. It is the objective of this study to determine the characteristics of this antenna, so that one can compute the response of the antenna to an incident EMP when the antenna is deployed in a tactical configuration.

1.2. Method of Analysis

The properties of LP antennas have been discussed in a number of textbooks. Mittra[1] describes the approach for studying these antennas in terms of a detailed analysis of the propagation properties of waves along the LP structure. The circuit-and-array approach is discussed in detail by Ma.[2] The second of these approaches has recently been applied[3] to a five-element LP array to compute the impulse response of such an antenna.

Each of the above theoretical approaches requires a considerable amount of analysis and computer programming to determine the solution. Furthermore, the theoretical solutions are carried out for idealized geometries, i.e., antennas in free space. An EMP vulnerability assessment, on the other hand, necessitates solutions for responses of antennas as they are used in communications systems. For these reasons, the characteristics of the AS-2169 were determined from experimental data, and a semiempirical model of the antenna was then developed based on these measurements.

2. EXPERIMENTAL ANALYSIS

2.1. Description of Continuous-Wave Facility

We present here a brief description of the continuous-wave (CW) test facility (fig. 1) since it was used for making most of the measurements on the antenna. The facility basically consists of a set of horizontal and vertical transmit antennas for generating the incident field and instrumentation for measuring the antenna response relative to the incident field. The transient response of the antenna is determined from Fourier inversion of the CW data.

The operation of the facility is automated to the extent that the frequency synthesizer is under control of the Hewlett-Packard (HP) 9820 calculator, and the output from the network analyzer is read by the calculator. Under normal operation, the calculator commands the synthesizer to sweep over a given frequency range at a specified frequency increment. The minimum and maximum frequencies are chosen so that the peak amplitudes of the response fall well within these frequency limits, and the frequency increment is selected to provide for adequate resolution of the response in the frequency domain.

[1] R. Mittra, Log-Periodic Antennas, Antenna Theory, Part 2, edited by R. E. Collin and F. J. Zucker, McGraw-Hill, Inc., New York (1969), 349–385.

[2] M. T. Ma, Theory and Application of Antenna Arrays, John Wiley and Sons, New York (1974).

[3] F. J. Solman, III, Time Domain Response of Wire Antenna Arrays, United States National Committee-International Union of Radio Science (USNC-URSI) Meeting, University of Illinois, Urbana (June 1975).

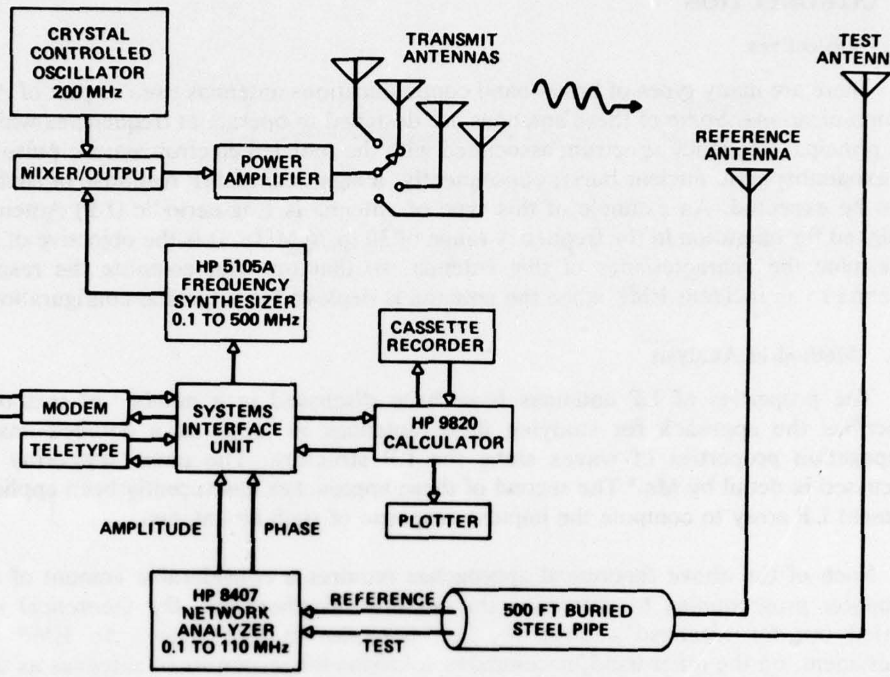

Figure 1. Continuous-wave test facility.

The CW data are normally recorded on cassette tapes and plotted on the HP plotter. Once recorded, the data can be transferred at some convenient time later to a Control Data Corp. (CDC) 6600 computer for subsequent data analysis. Figure 2 shows the frequency synthesizer and network analyzer in the foreground and the cassette recorder, the calculator, and the plotter in the background.

Two types of measurements are normally made. First, one usually measures the terminal response of the antenna relative to the field incident on the antenna; this is sometimes referred to as the transfer function or effective height of the antenna. Second, one typically measures the antenna input impedance. The transfer function is determined from two separate measurements: (1) the response of the antenna relative to a reference antenna and (2) the incident field at the location of the test antenna (in the absence of this antenna) relative to the reference antenna. The transfer function is then given by the ratio of these two measurements. The antenna impedance is measured directly by operating the antenna in the transmit mode and measuring the voltage at the antenna input in the reference channel and the corresponding antenna input current in the test channel.

2.2. Measurements on Log-Periodic Antenna

When the antenna is used in a tactical configuration, it is normally supported by an aluminum mast (fig. 3). It is well known that the antenna has a high directivity in the plane of the antenna (along the locus of midpoints from the long elements to the short elements). To illustrate

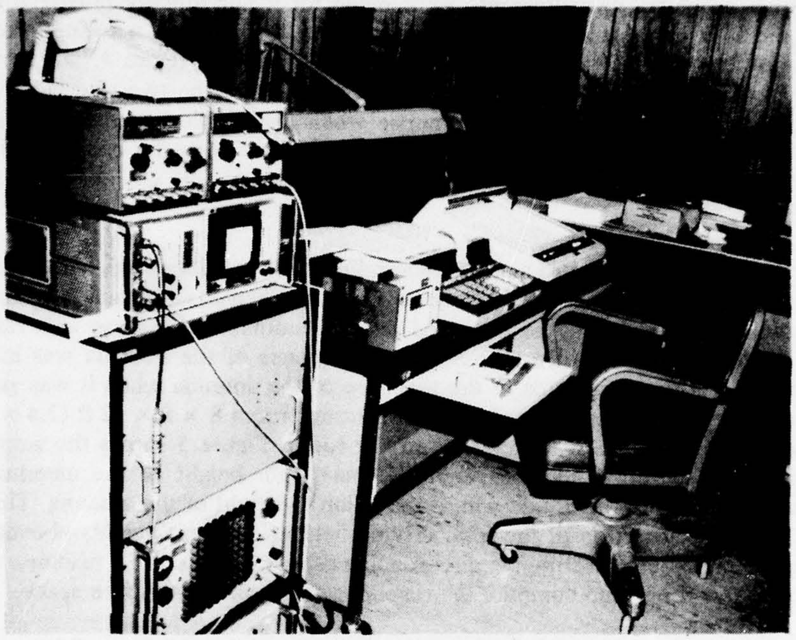

Figure 2. Instrumentation for continuous-wave test.

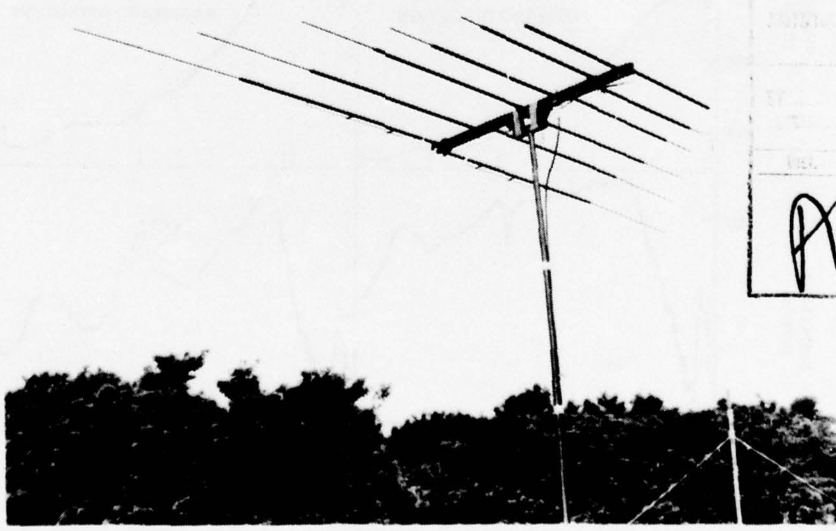

Figure 3. Log-periodic antenna (frequency range: 30 to 76 MHz).

this directional property, measurements were made for a horizontally polarized field incident from both the forward and backward directions when the antenna was supported on a 16-ft wooden mast. The results of these measurements are shown in figure 4, wherein pronounced differences in the amplitudes of the responses are evident for the two directions of incidence. The antenna has a higher broad-band response when the smallest element is pointing in the direction of the incident wave. (This is sometimes referred to as the backfire direction.) This direction of incidence also results in a maximum response for the case of a transient incident field.

The geometry for the forward and backward directions was idealized, since the antenna was far from ground and any other conducting scatterers. When the antenna is used as part of a communications system, it may be deployed on an aluminum mast close to a radio-frequency (rf) signal shelter. The effect of a shelter on the response of the antenna was investigated by making a number of measurements of the response of the antenna when it was supported on a mast near such a shelter. The shelter used was a screen room 8 × 8 × 12 ft (2.4 × 2.4 × 3.7 m) with the antenna above one of the corners of the room. Figure 5 shows the amplitudes of the responses relative to the incident field at the maximum height of the antenna. The major variation is a reduction in amplitude with a reduction in height of the antenna. This variation is primarily due to the variation of the total driving field at different heights aboveground. From these measurements, one can compute a reasonable estimate of the EMP response of an antenna near such a shelter if one can compute the response of the antenna in free space.

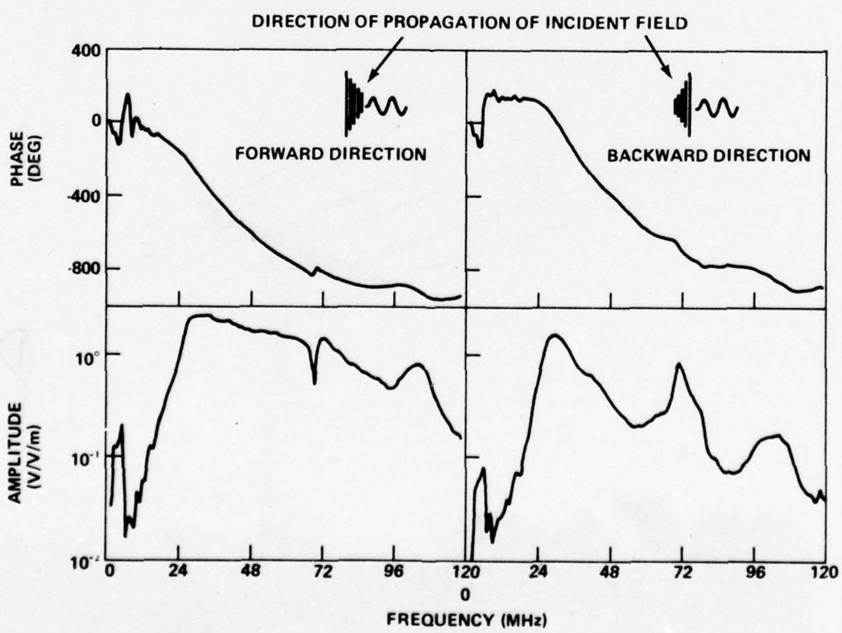

Figure 4. Continuous-wave data for log-periodic antenna.

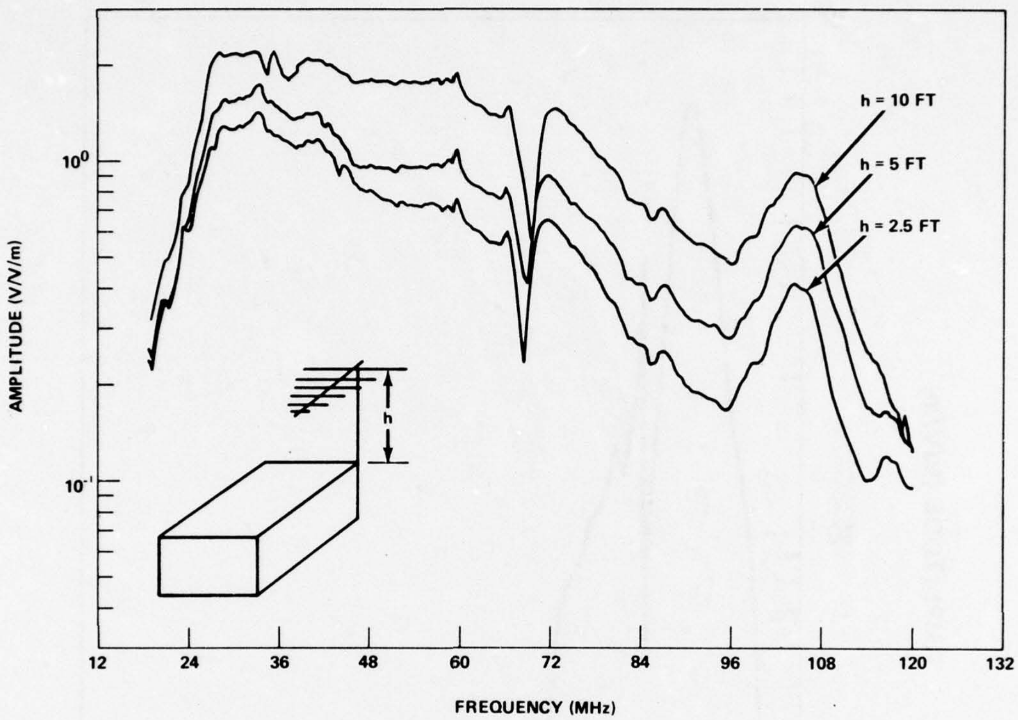

Figure 5. Continuous-wave data for log-periodic antenna near radio-frequency shelter.

Not normally considered in the analysis of an LP antenna is the response of such an antenna to a vertically polarized incident field. This response must be considered for an EMP vulnerability assessment, because the aluminum mast on which the antenna is supported also behaves like a receiving antenna. Figure 6 shows the results of a CW measurement at the output of the antenna cable when the antenna is on a 16-ft mast for vertical polarization. The mast behaves like a ¼-wavelength monopole antenna, and it can contribute a large, low-frequency signal to the response of the antenna and its cable.

To completely characterize the antenna, one must know the antenna impedance. Figure 7 shows the input impedance at a 40-ft cable attached to the antenna. Over the operating range of the antenna, the input impedance can be approximated reasonably well by a real 50-Ω resistance. A set of measurements was made of the antenna's transient response for evaluating the computation of the antenna's transient response by using CW data. The antenna was illuminated by a horizontally polarized pulse from an EMP simulator, and measurements were made of the responses of the antenna at the output of the antenna cable. The measured incident horizontal electric (E)-field component is shown in figure 8, and the measured transient response to this field is shown in figure 9. Also shown in figure 9 are the transient responses computed from CW data (sect. 3). The incident field was measured at the location of the antenna in the absence of the antenna and its support structure. This measurement was made by using an electrically small, capacitively top-loaded monopole antenna supported on a small instrumentation box containing the power supply and instrumentation for the measurement.

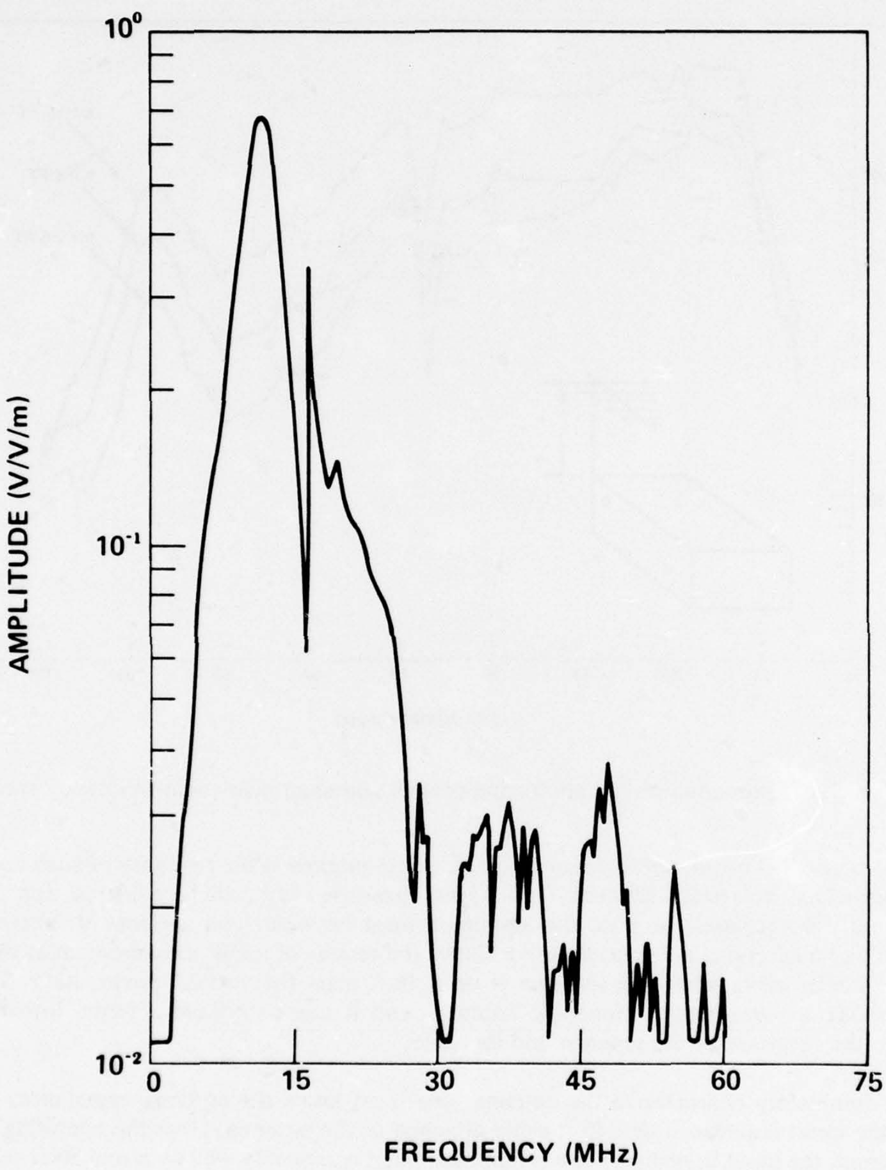

Figure 6. Continuous-wave data for log-periodic antenna for vertically polarized incident field.

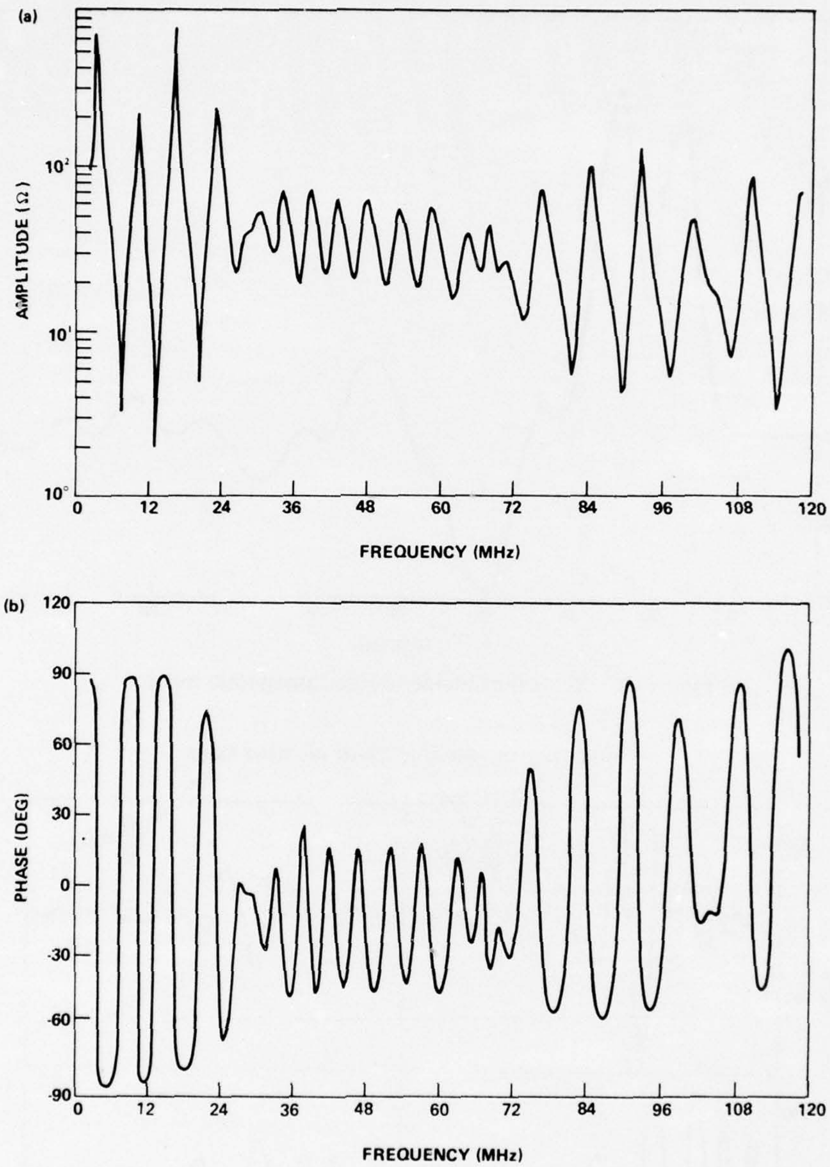

Figure 7. Input impedance of log-periodic antenna: frequency spectrum (a) amplitude and (b) phase.

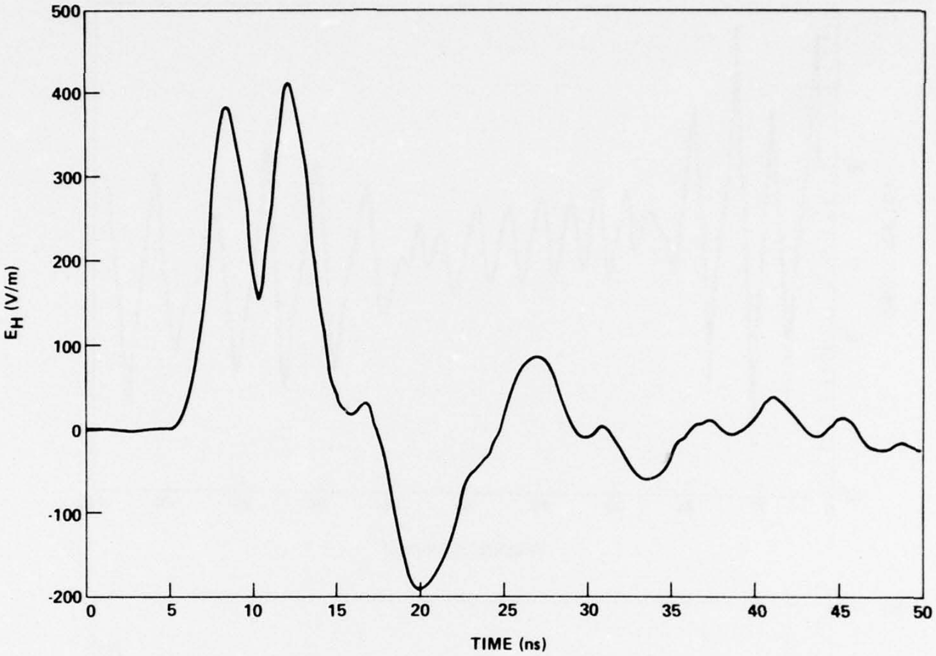

Figure 8. Transient incident electromagnetic pulse.

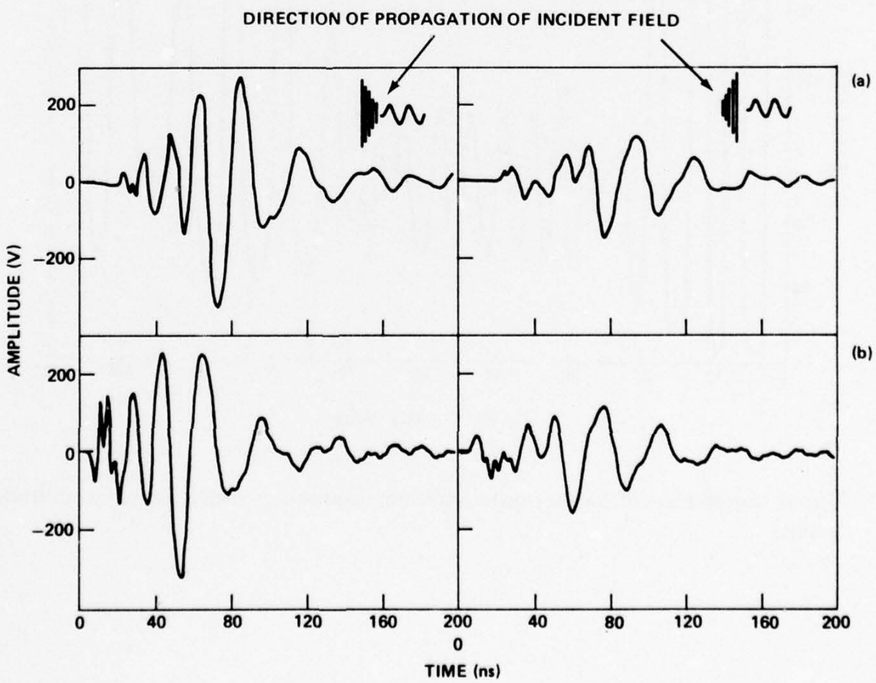

Figure 9. Transient response of log-periodic antenna: (a) measured and (b) computed from continuous-wave data.

3. EQUIVALENT CIRCUIT FOR LOG-PERIODIC ANTENNA

3.1. Semiempirical Model for Antenna Response

The LP antenna and the cable attached to it are completely characterized when the output of the cable is described in terms of the Thévenin equivalent circuit shown in figure 10.

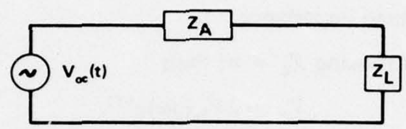

Figure 10. Thévenin equivalent circuit for log-periodic antenna.

In this figure, $V_{oc}(t)$ is the open-circuit voltage response of the antenna and the cable to an incident electromagnetic field, Z_A is the network representing the input impedance of the cable at the receiver end with the antenna at the far end, and Z_L is the network representing the receiver. We can write Z_A in the frequency domain as

$$Z_A(j\omega) = Z_0 \frac{1 + R(j\omega)e^{-2\Gamma l}}{1 - R(j\omega)e^{-2\Gamma l}} , \qquad (1)$$

where

$j\omega$ = complex radian frequency,

Z_0 = characteristic impedance of cable attached to antenna,

$$R(j\omega) = \frac{Z_{LP}(j\omega) - Z_0}{Z_{LP}(j\omega) + Z_0},$$

$$\Gamma = j\frac{\omega}{c} + \alpha,$$

l = length of cable attached to antenna,

Z_{LP} = input impedance of antenna,

α = attenuation constant.

This antenna impedance cannot easily be represented by a network over a wide range of frequencies. For the antenna under investigation, we can simplify equation (1) for the following reasons. First, we see from figure 7 that over the operating range of the antenna, the cable and antenna are well matched, so that for that range $|R(j\omega)| \ll 1$. Second, the term $e^{-2\Gamma l}$ in equation (1) corresponds to a time delay of approximately 80 ns for a 30-ft cable; hence, the effects of any mismatch conditions at the antenna termination are not seen until after that time delay and do not affect the initial portion of the transient response. Then the antenna impedance in equation (1) simplifies to

$$Z_A(j\omega) \simeq Z_0 . \qquad (2)$$

With the above approximation for Z_A, the voltage across a linear load at the output of the cable, $V_L(j\omega)$, can be written as[4]

$$V_L(j\omega) = V_{Z_0}(j\omega)(1 + \rho)e^{-\Gamma l} \qquad (3)$$

[4] S. Goldman, Laplace Transform Theory and Electrical Transients, Dover Publications, Inc., New York (1966).

where

$$V_{Z_0}(j\omega)e^{-\Gamma l} = \text{voltage into matched impedance at output of cable},$$

$$\rho = \frac{Z_L - Z_0}{Z_L + Z_0},$$

$$Z_L = \text{load impedance}.$$

We obtain V_{oc} from equation (3) using $Z_L = \infty$; then

$$V_{oc} = 2V_{Z_0}(j\omega)e^{-\Gamma l}. \tag{4}$$

The problem of adequately characterizing the antenna to estimate its EMP response reduces to a determination of the induced voltage for a matched impedance load, at the output of the antenna cable.

There are several analytical methods for computing the response of an LP antenna; however, we want to investigate the possibility of developing a simple semiempirical model for this antenna. We can see from the experimental data that the antenna response for the forward direction of incidence is a rather slowly varying function in phase and amplitude over the operating range of the antenna. It should not be difficult, therefore, to fit such a function with a simple analytical expression for the antenna response.

The simplest possible model for the antenna is to assume that the dipole elements of the antenna are weakly coupled to one another and behave primarily as uncoupled dipole antennas. Admittedly, this is a crude approximation to a rather complex problem; however, we shall see that for a vulnerability assessment, this approximation suffices. By this approximation, the frequency domain solution for the antenna is of the form

$$V_{LP}(j\omega) = \sum_{i=1}^{N} (-1)^{N-1} V_i(j\omega)e^{-2j\omega d_i} \tag{5}$$

where

$V_{LP}(j\omega)$ = output voltage of antenna,

N = number of dipole elements,

$V_i(j\omega)$ = output voltage of ith dipole element,

d_i = distance of ith dipole element from shortest element.

The output voltage referred to is the voltage into a matched impedance load at the output of the coaxial cable connected to the antenna. The term $(-1)^{N-1}$ accounts for the fact that the dipoles for the antenna are connected to the balanced feeder line in a phase-reversal fashion. The phase factor $e^{-2j\omega d_i}$ accounts for the phase relationship of the responses of the dipole elements relative to the shortest element, i.e., to the output of the antenna.

There are innumerable approaches to the solution of the response of a dipole antenna. For the present purposes, we do not require a highly accurate solution and simply use a solution based on the transmission line analogy of a dipole antenna (app A). The dipole terms in equation (1) are then given by

$$V(j\omega) = \frac{E}{\Gamma}(1 + R_1)\frac{[1 - (1 + R_2)e^{-\Gamma l} + R_2 e^{-2\Gamma l}]}{1 + R_1 R_2 e^{-2\Gamma l}}, \tag{6}$$

where

E = electric-field component of incident field,

R_i = reflection coefficients,

l = halflength of dipole.

The lengths of the elements to be used in equation (6) and the separation distances in equation (7) correspond to physical dimensions of an LP antenna. A reasonable estimate of these dimensions can be made if one knows the operating range of the antenna and the separation between the smallest and largest elements. The smallest and largest half lengths correspond to approximately ¼ wavelength of the maximum and minimum operating frequencies, respectively. The lengths of the remaining elements can then be determined from the knowledge that adjacent lengths of the dipole elements form a geometric progression with a common ratio τ:[5]

$$\frac{l_i}{l_{i+1}} = \tau, \qquad i = 1, 2, \ldots, N - 1;$$

the distances between adjacent elements is given by[5]

$$\Delta_i = l_i(1 - \tau)(\cot \alpha)/\tau, \qquad i = 1, 2, \ldots, N, \tag{7}$$

where $\tan \alpha = (l_N - l_1)/d$, with d being the separation between the longest and shortest element. Then d_i in equation (5) is given by the sum of the various separation distances. The reflection coefficients R_1 and R_2 in equation (6) are real numbers with $R_1 \simeq -0.9$ and $R_2 \simeq 1$. The best value of R_1 for the antenna under investigation was determined by comparing the computed antenna response with CW measurements.

3.2. Analytical Computations of Antenna Response

If the amplitude of the CW excitation is held fixed over the frequencies of interest, the in-band response of the antenna necessarily is much greater than the out-of-band response; this difference is clearly indicated by the CW measurements shown in figure 4. Thus, since the major spectral content of the antenna's response is confined in a relatively narrow band, the inverse Fourier transform of the measured CW transfer function is a good approximation to the impulse response of the antenna. Once the impulse response has been computed, it is straightforward to obtain the transient response of the antenna for an EMP excitation with the same polarization and direction of propagation as the CW excitation used in the experiments. That is, we merely perform a convolution of the incident field in figure 7 with the impulse response which was computed, in turn, from the CW data shown in figure 4.

For an EMP vulnerability assessment, we are interested in the response of the antenna to a horizontally polarized EMP such as shown in figure 11, arriving at a given angle with respect to ground. To compute the antenna response, we compute the total incident field—i.e., the sum of the incident and ground reflected fields—and convolve this with the impulse response. Figure 12 shows the total incident field for an angle of incidence of 45 deg at a height of 10 m above ground. The response of the antenna to this field is shown in figure 13. The agreement is reasonably good, so that one might rely on the model predictions for a similar antenna in lieu of experimental data.

[5] D. E. Isbell, Log-Periodic Dipole Arrays, IRE Trans. Antennas and Propagation, *AP-8* (May 1960), 260–267.

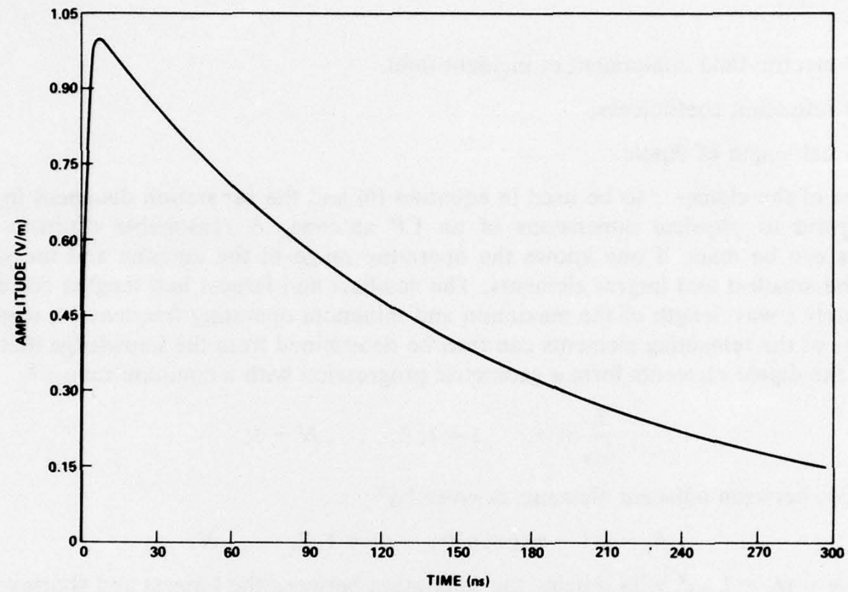

Figure 11. Incident electromagnetic pulse.

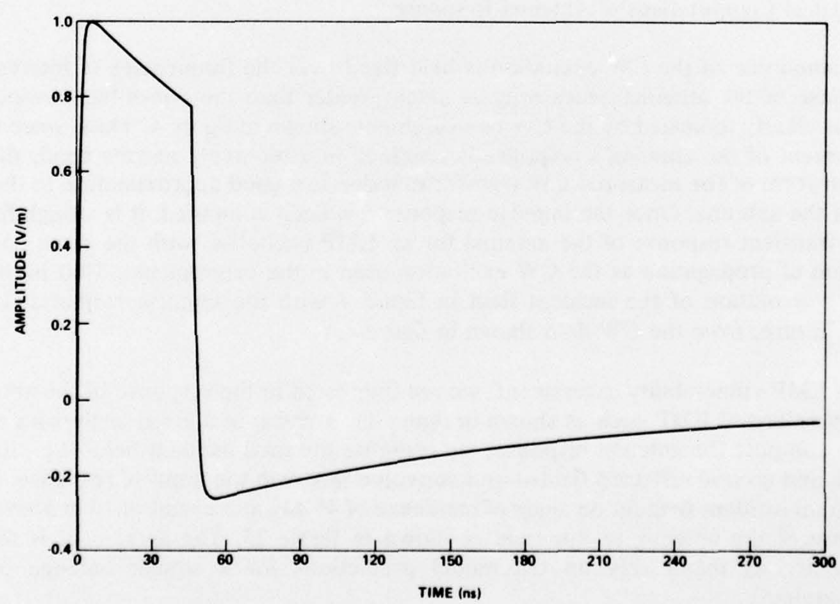

Figure 12. Total electromagnetic pulse after ground interaction.

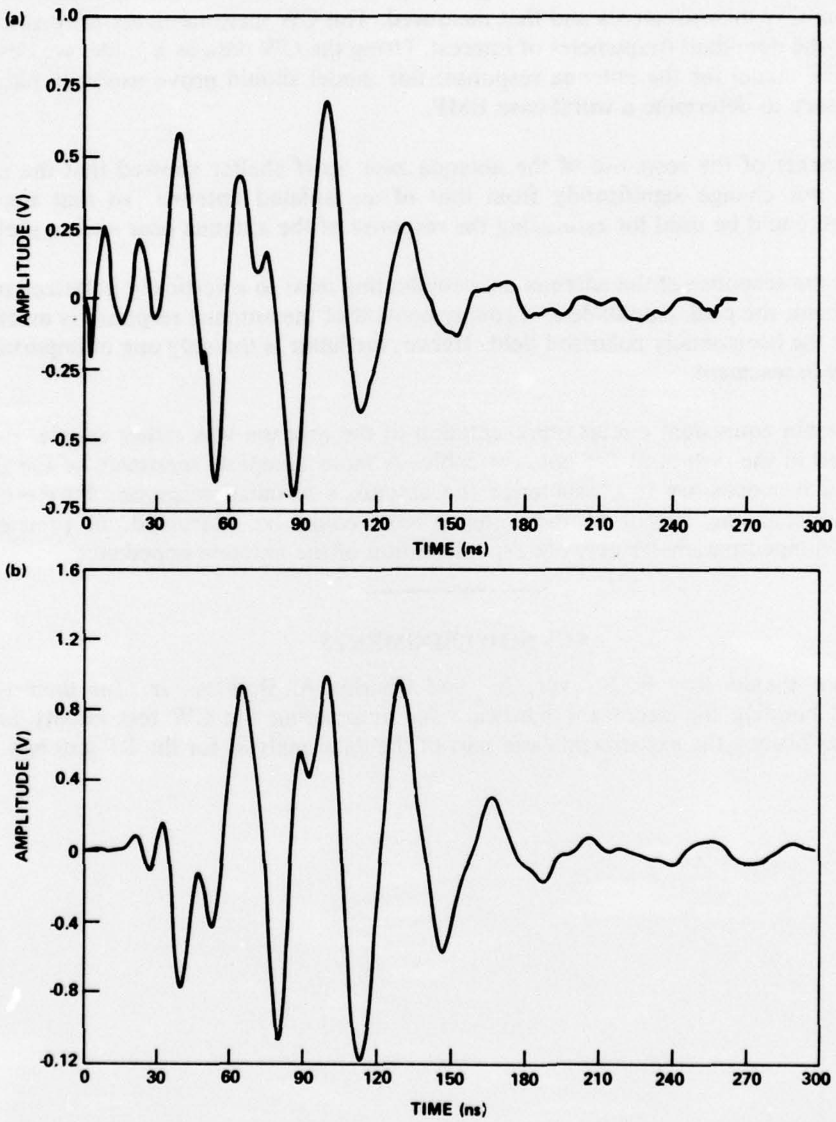

Figure 13. Log-periodic antenna transient response to total electromagnetic pulse: computed from (a) continuous-wave data and (b) analytical model.

4. CONCLUSIONS AND RECOMMENDATIONS

The EMP response characteristics of LP antenna AS-2169 were determined from both CW and transient measurements. There was good agreement between the transient response computed from CW measurements and that measured. The CW measurements were sufficiently accurate over the dominant frequencies of interest. Using the CW data as a guide, we developed a semiempirical model for the antenna response; this model should prove useful in parametric studies necessary to determine a worst-case EMP.

Measurements of the response of the antenna near an rf shelter showed that the antenna response did not change significantly from that of an isolated antenna, so that the model developed here could be used for estimating the response of the antenna near such a shelter.

Although the response of the antenna on a conducting mast to a vertically polarized incident field is significant, the peak amplitude and energy content of the antenna response is much lower than those for the horizontally polarized field. Hence, the latter is the only one of importance for a vulnerability assessment.

The Thévenin equivalent circuit representation of the antenna was rather simple, since we were interested in the output at the antenna cable. A more complete treatment of the isolated antenna would be necessary to characterize the antenna's terminal response. Furthermore, a nonlinear load near the output of the antenna also could be addressed, in principle, by determining a lumped-parameter-network representation of the antenna impedance.

ACKNOWLEDGMENTS

The author thanks Roy E. Strayer, Jr., and Charles A. Berkley, Jr., for their work in designing and building the necessary hardware for automating the CW test facility and Mr. Berkley for performing the experiments and part of the data analysis for the LP antenna.

APPENDIX A.

APPROXIMATE RESPONSE OF A CYLINDRICAL DIPOLE ANTENNA

A-1. INTRODUCTION

These steps were used in deriving the solution to the problem of the dipole antenna:

1. Discuss how the current distribution on a driven two-wire transmission line is approximately analogous to the current distribution on a dipole antenna.
2. Derive the current distribution on the antenna using the transmission-line analogy.
3. Knowing the current distribution, compute the radiated fields.
4. Apply reciprocity to determine the received signals.

A-2. TRANSMISSION-LINE ANALOGY

Schelkunoff and Friis[1] discuss well how currents on a transmission line are analogous to currents on an antenna. Basically, one can show that the input impedance of a symmetric biconical antenna of any angle can be described in a similar manner as the input impedance of a uniform transmission line whose length equals the length of one antenna arm. The same similarity holds for antennas of other shapes such as cylindrical antennas, the main difference being nonuniformity of the equivalent line. Schelkunoff[2] has shown also that, for a cylindrical antenna, one can derive an average characteristic impedance which can be used in determining the input impedance of an antenna. This input impedance can be determined accurately by using nonuniform transmission-line theory; however, in the following discussion we will make a further approximation of applying uniform transmission-line theory for computing the antenna impedance.

A-3. CURRENT DISTRIBUTION ON DIPOLE ANTENNA

Consider a dipole antenna oriented along the x-axis as shown in figure A-1.

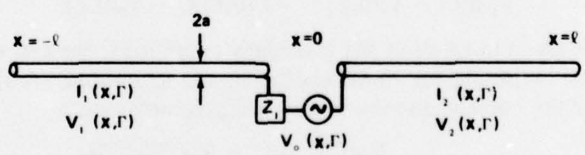

Figure A-1. Driven dipole antenna in free space.

From the symmetry of the problem, we can place a ground plane at $x = 0$ perpendicular to the antenna, with voltages V_1 and V_2 being measured relative to this ground plane. Using the transmission-line analogy for the dipole, we have a termination impedance of $Z_2/2$ at $x = \pm l$ relative to this ground plane, where l is the half length of the dipole. With these assumptions, we

[1] S. A. Schelkunoff and H. T. Friis, Antennas—Theory and Practice, John Wiley and Sons, Inc., New York (1966).
[2] S. A. Schelkunoff, Advanced Antenna Theory, John Wiley and Sons, Inc., New York (1952).

get the following general solutions for the currents and voltages:

$$I_1(x,\Gamma) = A_1 e^{-\Gamma x} - B_1 e^{\Gamma x} \tag{A-1}$$

$$I_2(x,\Gamma) = A_2 e^{-\Gamma x} - B_2 e^{\Gamma x} \tag{A-2}$$

$$V_1(x,\Gamma) = \tfrac{1}{2}Z_0 A_1 e^{-\Gamma x} + \tfrac{1}{2}Z_0 B_1 e^{\Gamma x} \tag{A-3}$$

$$V_2(x,\Gamma) = \tfrac{1}{2}Z_0 A_2 e^{-\Gamma x} + \tfrac{1}{2}Z_0 B_2 e^{\Gamma x} \tag{A-4}$$

where

X = position along the antenna

$\Gamma = \sqrt{YZ}$, propagation constant,

$\tfrac{1}{2}Z_0 = \sqrt{Z/Y}$, characteristic impedance,

$A_{1,2}, B_{1,2}$ = unknown coefficients,

Z, Y = impedance and admittance relative to ground plane.

Our approximation will be that we can represent Γ and Z_0 as

$$\Gamma \simeq \frac{j\omega}{c} + \alpha, \quad \text{propagation constant for lossy transmission line,}$$

$$Z_0 \simeq 120\left[\ln\frac{2l}{a} - 1\right], \quad \text{average characteristic impedance of cylindrical dipole.}$$

The boundary conditions for the problem are the following:

$$V_1(-l,\Gamma) = -I_1(-l,\Gamma)Z_2/2$$

$$V_2(l,\Gamma) = I_2(l,\Gamma)Z_2/2$$

$$I_1(0,\Gamma) = I_2(0,\Gamma)$$

$$V_2(0,\Gamma) - V_1(0,\Gamma) = -I_1(0,\Gamma)Z_1 + V_0(0,\Gamma).$$

Substituting equations (A-1) to (A-4) in the boundary conditions, we can solve for the unknown coefficients. Finally, substituting for these coefficients in equations (A-1) to (A-4), we get the desired expression for the current distribution on a dipole antenna:

$$I_1(x,\Gamma) = \frac{V_0(0,\Gamma)}{(Z_1 + Z_0)} \frac{[e^{\Gamma x} - R_2 e^{-2\Gamma l} e^{-\Gamma x}]}{(1 - R_1 R_2 e^{-2\Gamma l})}, \tag{A-5}$$

$$I_2(x,\Gamma) = \frac{V_0(0,\Gamma)}{(Z_1 + Z_0)} \frac{[e^{-\Gamma x} - R_2 e^{-2\Gamma l} e^{\Gamma x}]}{(1 - R_1 R_2 e^{-2\Gamma l})}, \tag{A-6}$$

where

$$R_{1,2} = \frac{Z_{1,2} - Z_0}{Z_{1,2} + Z_0}, \quad \text{reflection coefficients.}$$

Many textbooks discuss the current distribution on a transmitting antenna in terms of a sinusoidal distribution:

$$I(x,\beta) = I_0 \sin \beta(l - x), \qquad x > 0,$$
$$= I_0 \sin \beta(l + x), \qquad x < 0,$$

where

$$\beta = j\omega.$$

We can get this form from equations (A-5) and (A-6) if we let $\Gamma = j\beta$, $R_2 = 1$, and

$$I_0 = \frac{2jV_0(0,\beta)}{(Z_1 + Z_0)(e^{j\beta l} - R_1 e^{-j\beta l})}, \qquad \text{current at antenna terminals.}$$

Our solutions in equations (A-5) and (A-6) are, therefore, more complete in the sense that the effect of the radiation resistance of the dipole can be taken into account with R_2 and that I_0 includes the effect of the load impedance. The inclusion of this effect becomes important for the receive properties of a dipole antenna.

A-4. RADIATED FIELDS FROM DIPOLE ANTENNA

In computing the radiated fields from a dipole antenna, we use a procedure discussed in many textbooks. First, we compute the vector potential knowing the current distribution on the dipole. Second, we get the magnetic field from

$$\vec{H} = \frac{1}{\mu_0} \vec{\nabla} \times \vec{A}, \tag{A-7}$$

and the electric field vector, $\vec{E}$, from

$$\frac{\partial \vec{E}}{\partial t} = \frac{\vec{\nabla} \times \vec{H}}{\epsilon_0}. \tag{A-8}$$

The vector potential from a given current distribution, $I(x)$, on the antenna can be written as

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{I(\vec{x}')e^{-\Gamma|\vec{r}-\vec{x}'|}}{|\vec{r} - \vec{x}'|} d\vec{x}', \tag{A-9}$$

where $\vec{r}$ is the radius vector to the point of observation. This integral is usually solved in terms of a multipole expansion for the kernel

$$\frac{e^{-\Gamma|\vec{r}-\vec{x}'|}}{|\vec{r} - \vec{x}'|}.$$

In applying this solution to the dipole antenna shown in figure A-1, we are interested only in the radiation in the $y-z$ plane at $x = 0$ (in polar co-ordinates, $\theta = \pi/2$, using the x-axis as the polar axis). Then we get a simple expression for the vector potential in the dipole approximation:

$$A_x(x=0) = \frac{\mu_0}{4\pi} \frac{e^{-\Gamma r}}{r} \int_{-l}^{l} I(x')\, dx'. \tag{A-10}$$

APPENDIX A

Substituting for $I(x')$ from equations (A-5) and (A-6), we get

$$A_x(x=0) = \frac{\mu_0 e^{-\Gamma r}}{2\pi r} \frac{V_0(0,\Gamma)}{(Z_L + Z_0)} \frac{[1 - (1 + R_2)e^{-\Gamma l} + R_2 e^{-2\Gamma l}]}{(1 - R_1 R_2 e^{-2\Gamma l})}. \tag{A-11}$$

Using this vector potential in equation (A-7), we obtain

$$H_\phi(\theta=90°) = \frac{\Gamma e^{-\Gamma r}}{2\pi r} I_0(0,\Gamma) \left(1 + \frac{1}{\Gamma r}\right) h(\Gamma,l,R_2), \tag{A-12}$$

$$E_\theta(\theta=90°) = \frac{\eta_0 \Gamma e^{-\Gamma r}}{2\pi r} I_0(0,\Gamma) \left[1 + \frac{1}{\Gamma r} + \frac{1}{(\Gamma r)^2}\right] h(\Gamma,l,R_2), \tag{A-13}$$

where

$$I_0(0,\Gamma) = \frac{V_0(0,\Gamma)}{(Z_L + Z_A)}, \tag{A-14}$$

$$Z_A = Z_0 \frac{1 + Re^{-2\Gamma l}}{1 - Re^{-2\Gamma l}} \tag{A-15}$$

η_0 = free-space wave impedance

$$h(\Gamma,l,R_2) = \frac{1}{\Gamma} \frac{[1 - (1 + R_2)e^{-\Gamma l} + R_2 e^{-2\Gamma l}]}{(1 - R_2 e^{-2\Gamma l})}. \tag{A-16}$$

A-5. RECEIVED SIGNALS OF CYLINDRICAL DIPOLE ANTENNA

The radiated far field of an antenna can be written in the form[3]

$$\vec{E} = \frac{j\beta\eta_0 I_0 e^{-j\beta r}}{4\pi} \vec{H}, \tag{A-17}$$

where

I_0 = current at the antenna terminals,

$\vec{H}$ = effective vector length of the antenna.

Then the open-circuit received voltage[4] (V_{oc}) is given by

$$V_{oc} = \vec{E} \cdot \vec{H}. \tag{A-18}$$

Equation (A-13) reduces to the form shown in equation (A-17) if we consider the far-field term only and let $\Gamma = j\beta$ and $2h\vec{i} = \vec{H}$ where $\vec{i}$ is a unit vector along the x-axis.

It is interesting to compare our solutions for the antenna height and antenna impedance with more complete solutions based on nonuniform transmission-line theory. The major differences are that, for the nonuniform transmission-line theory, we can obtain an accurate expression for

[3] G. Sinclair, The Transmission and Reception of Elliptically Polarized Waves, Proc. IRE, *38* (February 1950), 148–151.

[4] R. E. Collin, The Receiving Antenna, Antenna Theory, Part 1, edited by R. E. Collin and F. J. Zucker, McGraw-Hill, Inc., New York (1969), 105.

R_2 in equations (A-15) and (A-16), whereas from uniform transmission-line theory we expect a value of $R_2 \simeq 1$. Using $R_2 = 1$ and $\Gamma = j\beta$ in equation (A-16), we obtain the well-known effective length of an electrically small dipole antenna:

$$h = \frac{1}{\beta}\frac{(1 - \cos \beta l)}{\sin \beta l}.$$

In our approximation, the antenna impedance and the effective height are given by equations (A-15) and (A-16), respectively. Using equation (A-18), we obtain the expressions for the received current at the load impedance,

$$I_L(j\omega) = \frac{2E_x h}{Z_L + Z_A}, \tag{A-19}$$

and for the received voltage at the load impedance,

$$V_L(j\omega) = I_L(j\omega) Z_L. \tag{A-20}$$

This solution can be rewritten in terms of R_1 and R_2 as

$$I_L(j\omega) = \frac{E(j\omega)}{\Gamma Z_0}(1 - R_1)\frac{[1 - (1 + R_2)e^{-\Gamma l} + R_2 e^{-2\Gamma l}]}{(1 - R_1 R_2 e^{-2\Gamma l})}, \tag{A-21}$$

$$V_L(j\omega) = \frac{E(j\omega)}{\Gamma}(1 + R_1)\frac{[1 - (1 + R_2)e^{-\Gamma l} + R_2 e^{-2\Gamma l}]}{(1 - R_1 R_2 e^{-2\Gamma l})}. \tag{A-22}$$

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